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PETROLOGY OF THE DEVONIAN GAS-BEARING SHALE ALONG LAKE ERIE HELPS EXPLAIN GAS SHOWS

by

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PETROLOGY OF THE DEVONIAN GAS-BEARING SHALE ALONG LAKE ERIE HELPS EXPLAIN GAS SHOWS

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ABSTRACT

Comprehensive petrologic study of 136 thin sections of the Ohio Shale along Lake Erie, when combined with detailed stratigraphic study, helps explain the occurrence of its gas shows--most of which occur in the silty, greenish-gray, organic poor Chagrin Shale and Three Lick Bed. Both have thicker siltstone laminae and more siltstone beds than other members of the Ohio Shale and both units also contain more clayshales. The source of the gas in the Chagrin Shale and Three Lick Bed of the Ohio Shale is believed to be the bituminous-rich shales of the middle and lower parts of the underlying Huron Member of the Ohio Shale.

Eleven petrographic types were recognized and extended descriptions are provided of the major ones - claystones, clayshales, mudshales, and bituminous shales plus laminated and unlaminated siltstones and very minor marlstones and sandstones. In addition three major types of lamination were identified and studied. Thirty-two shale samples were analyzed for organic carbon, whole rock hydrogen and whole rock nitrogen with a Perkin-Elmer 240 Elemental Analyzer and provided the data base for source rock evaluation of the Ohio Shale.

Key Idea: *Shale petrology and CHN analyses, all closely integrated with the internal stratigraphy of the Devonian shales, help explain its stratigraphic distribution of gas shows.*

INTRODUCTION

Along Lake Erie (Fig. 1) the gas-bearing Devonian shales (Fig. 2) have produced marginal quantities of gas for over one-hundred years. The gas in these shales is largely associated with silt-rich lithologies in the Three Lick Bed of the Ohio Shale and in the Chagrin Shale (Fig. 3), as was recently demonstrated by Broadhead, Kepferle and Potter (1981), who also studied their internal stratigraphy and sedimentology.

We studied the petrology of the Ohio and Chagrin Shales to determine their composition, the number of petrographic types present in the different units, and, if possible, which of these types have the most significance for gas production. This report sets forth in full detail the petrology reported and summarized in Broadhead, Kepferle and Potter (1981) and is based on a Master of Science thesis by Broadhead (1979).

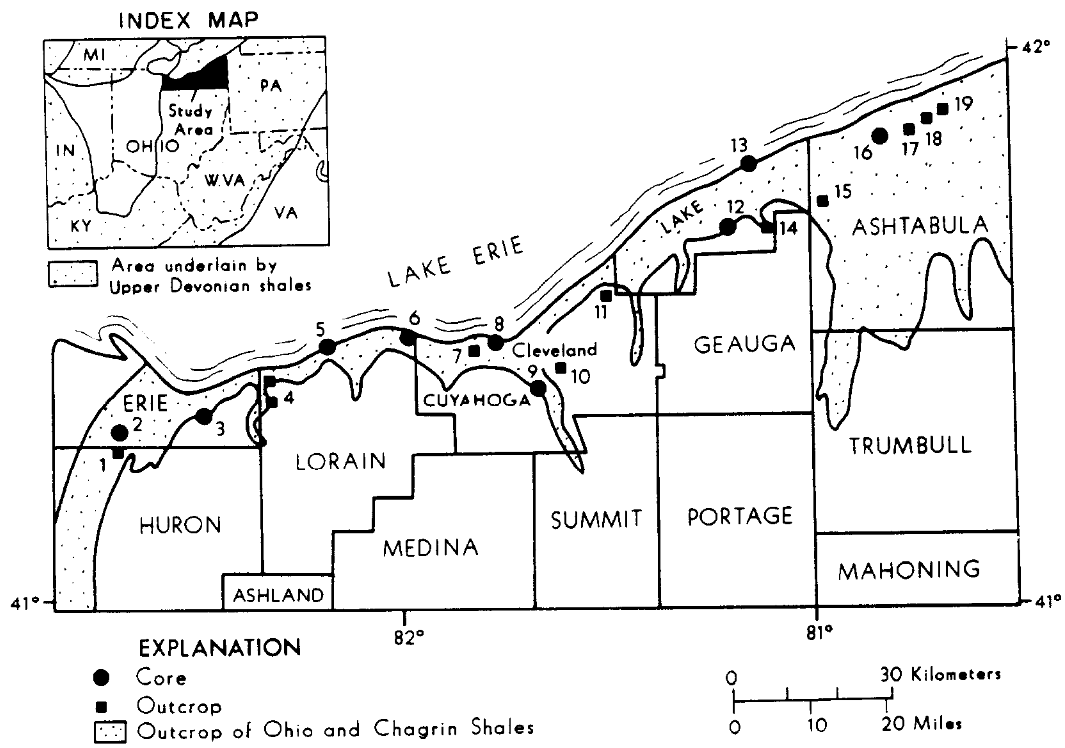

Figure 1. Index map of study area plus locations of studied outcrops and cores.

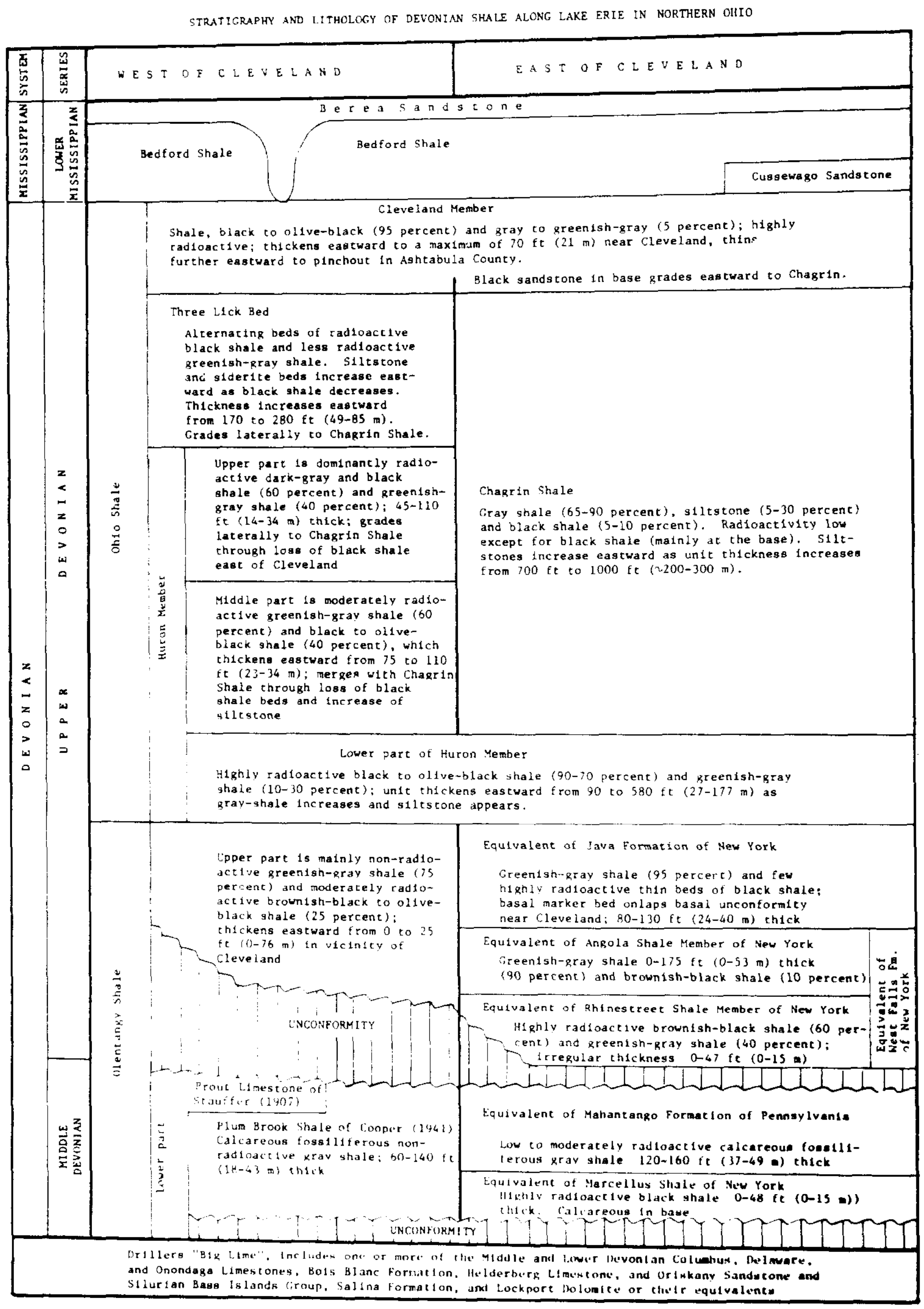

Figure 2. Stratigraphic section with detailed lithologic summary. Lithologic terms are field terms and hence their estimated proportions may differ from those of the petrographic types discussed in the text and summarized in Table 5.

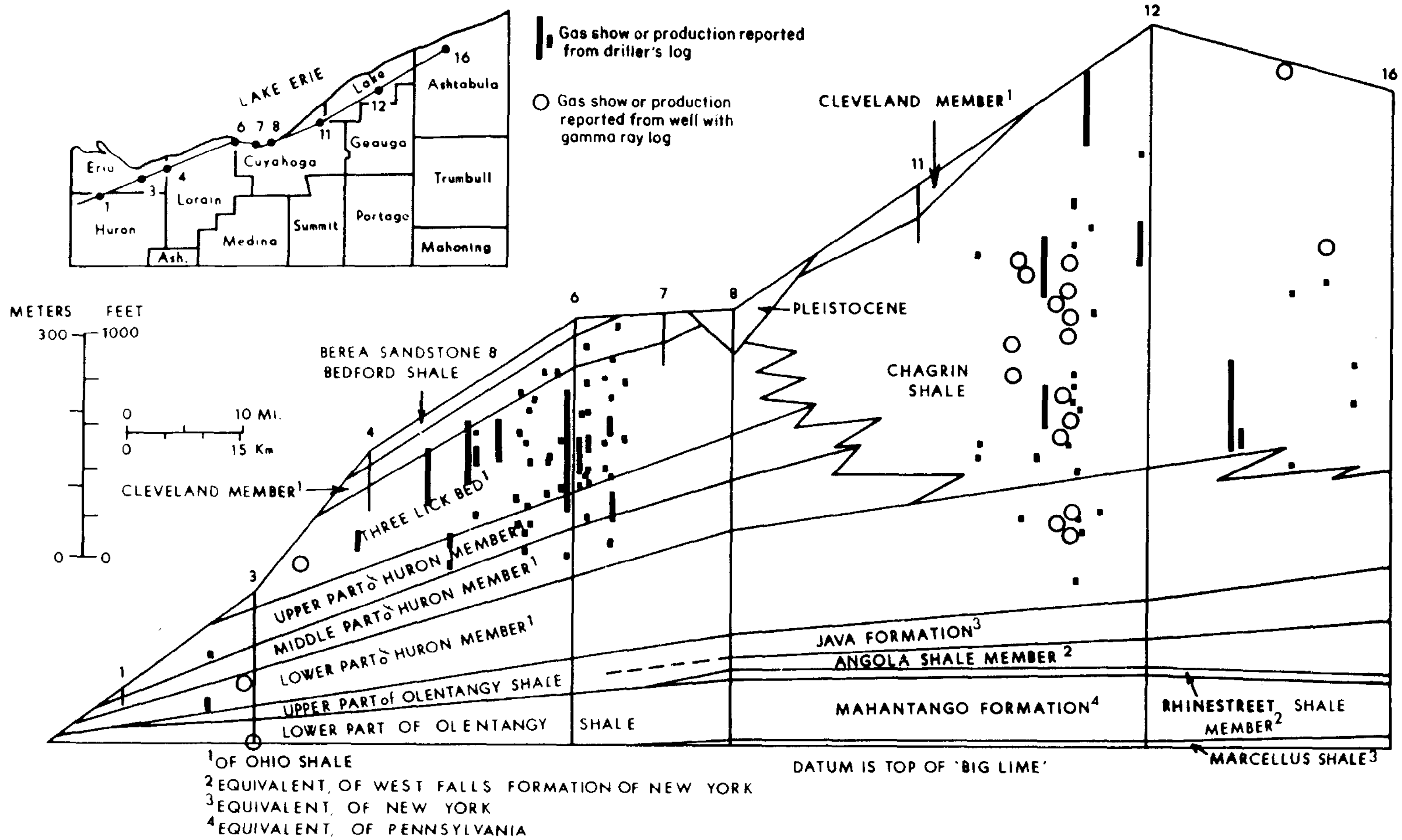

Figure 3. Northeast-southwest cross-section and projected gas shows from counties bordering Lake Erie. Data or gas shows obtained from files of Ohio Geological Survey, Columbus.

CONCLUSIONS

(1) Gas shows in the Ohio Shale along Lake Erie are controlled by sedimentary facies and are most abundant in the silty, greenish gray, organic poor parts of the Chagrin Shale and Three Lick Bed of the Ohio Shale, which contain thicker siltstone laminae, more siltstones and clay shale.

(2) The source of this gas may have been the underlying bituminous shales of the lower and middle parts of the Huron Member of the Ohio Shale.

(3) Lamination in gas bearing or potentially gas bearing shales deserves attention because it provides a layered system for gas delivery to the borehole, one that is far superior to that of a fully bioturbated and unlaminated shale

(4) Bituminous shale is the dominant lithology of the Cleveland Member of the Ohio Shale and of the middle and lower parts of the Huron Member and defines the carbon-rich part of the Ohio Shale.

(5) Clayshale is the dominant lithology of the Chagrin Shale and the upper part of the Huron Member of the Ohio Shale, whereas claystone and clayshale are the dominant lithologies of the Three Lick Bed and define the hydrogen-rich facies of the Ohio Shale.

(6) The Three Lick Bed of the Ohio Shale contains about 12 percent carbonate in the thin sections that we studied, which should perhaps be considered in well completion or well treatment.

(7) The Jaccard correlation coefficient (Till, 1974, p. 135; Cheetham and Hazel, 1969) was very helpful to estimate the correlations among the different types of lamination within a thin section and seems destined to play a larger role in shale petrology, because it was specifically designed for attributes--data which is either presence or absence--such as presence or absence of bioturbation in a thin section, presence or absence of pyrite nodules, lamination types, etc. In short, the Jaccard coefficient helps digest and reduce attribute data, so much of which plays an important part in assessing the gas potential of the different stratigraphic units that make up the Devonian shales of the Appalachian Basin.

METHODS

Thin-section petrology and X-ray diffraction were used. Thin-section petrology was emphasized because it is a rapid method for determining mineralogy and also effectively defines grain size, lamination, and cementation, which cannot be studied with X-ray diffraction. On the other hand X-ray diffraction is needed to identify the different clay and carbonate minerals. Larese and Heald (1977) and Nuhfer and Vinopal (1978) used thin-section and X-ray petrology to examine the Upper Devonian shales from West Virginia. Others who have notably published on the thin-section study of shales include Rubey (1931), Carozzi (1960, p. 124-189), Folk (1960) and Burger (1963). Rubey's pioneering study, with its emphasis on lamination (p. 40-48 and 51-52), deserves more attention from shale petrologists.

One hundred thirty-six thin sections were studied, of which seventy-one were point counted; 200 counts were made on each thin section at magnification of 500X using a Zeiss student microscope. Quartz plus feldspar, clay, mica, organics, *Tasmanites*, pyrite, carbonate, and other (heavy minerals, rock fragments, chert, bone fragments, and conodonts) were counted (Table 1). Quartz and feldspar were counted in one category because of the difficulty of differentiating between these two minerals in thin section; identifiable feldspar is never more than 1 percent of a thin section, and X-ray diffraction confirms that it occurs only in trace amounts. Compositions for some samples were estimated with visual comparator charts (Baccelle and Bosellini, 1965) and some samples were assigned rock names, but neither counted nor estimated. Coarsest grain size was defined as the average of the five longest apparent diameters of quartz grains in a thin section. Coarsest grain size provides an estimate of the maximum competence of currents and was routinely plotted against stratigraphic section.

AVERAGE PETROGRAPHIC COMPOSITION

The average petrographic composition of the different stratigraphic units varies markedly (Table 2). Organic material, as defined by thin sections, is most abundant in the dark shales of the middle and lower parts of the Huron Member of the Ohio Shale 21.8 and 20.8 percent, followed by the Cleveland Member of the Ohio Shale, 15.0 percent, whereas the Chagrin Shale has the least, only 2.8 percent. In contrast the average clay content of all the different units ranges from only 51.0 to 69.7 percent--very little variation for a dominant constituent. Two other notable features are the high carbonate content of the Three Lick Bed, 12.4 percent, and the high silt content, 21.3 percent of the Cleveland Member. The appendix contains a complete listing of all the data on which the averages of Table 2 are based.

In future petrologic studies it would be informative to make comparisons of the same stratigraphic units elsewhere in the Appalachians, carefully controlling operator variation, to determine how homogeneous they are, especially along their north-south depositional strike.

TABLE 1

SUMMARY OF SHALE COMPONENTS

Quartz: Subangular to very angular, equant to elongate, silt- to very fine sand-size grains; most quartz monocrystalline.

Feldspar: Angular, silt-size orthoclase and twinned plagioclase; fresh or slightly altered to clays.

Clay: Smaller than 0.01 mm; aggregates of illite and chlorite with aggregate polarization, aggregates elongate parallel to bedding and/or lamination; clays bent around quartz, feldspar, pyrite, *Tasmanites*, and opaque organics.

Mica: Larger than 0.01 mm; elongate chlorites, muscovite, and rare biotite; long axes of micas subparallel to bedding and/or lamination; most grain outlines sharp; micas bend around quartz, feldspar, pyrite, *Tasmanites*, and opaque organics.

Organic Material: Two types: (1) translucent, amorphous, orange to brown, irregular strands typically 0.02 mm long; bent around quartz, feldspar, clay, mica, pyrite, and *Tasmanites;* (2) opaque, amorphous, black material in equant to elongate fragments typically 0.05 mm long; many fragments partially pyritized.

Tasmanites: Yellow to orange hollow spheres made of amorphous, translucent organic material; sporelike; sphere wall typically 0.02 mm thick; most individuals crushed and elongate parallel to bedding and/or lamination; some not crushed and infilled with pyrite and/or chert before compaction, typically 0.2 mm in diameter; regarded by Sommer (1956, p. 180) as a fossil algae, probably pelagic (Wall, 1962, p. 360).

Pyrite: Euhedral to anhedral disseminated crystals, infillings of *Tasmanites*, and irregular patches in quartz laminae; disseminated crystals typically 0.01 mm in diameter; patches in quartz laminae typically 0.04 mm in diameter.

Carbonate: Anhedral to euhedral calcite, siderite, dolomite; occurs as isolated crystals in shale and as cement in quartz laminae and in siltstones and siltshales; crystals typically 0.02 mm to 0.05 mm in diameter; replaces quartz, locally extensively.

Other: Detrital, rounded, fine silt-size zircon and tourmaline, authigenic chert, bone fragments, and conodonts.

TABLE 2

AVERAGE PETROGRAPHIC COMPOSITION OF STRATIGRAPHIC UNITS

Stratigraphic Unit	Quartz plus Feldspar	Clay	Mica	Organics	Tasmanites	Pyrite	Carbonate	Other[2]
Ohio Shale								
Cleveland Member, 6[1]	21.3	54.6	3.1	15.0	T	5.8	T	T
Three Lick Bed, 16[1]	19.4	55.9	2.5	5.4	T	3.8	12.4	T
Upper part of Huron Member, 6[1]	14.0	61.0	1.2	13.8	1.2	4.7	3.2	T
Middle part of Huron Member, 5[1]	9.8	51.0	1.6	21.8	1.2	5.8	8.6	0
Lower part of Huron Member, 19[1]	13.3	52.2	3.1	20.8	1.3	7.0	2.5	T
Chagrin Shale, 21[1]	17.7	69.7	2.9	2.8	T	4.4	2.2	T

[1]Sample size.

[2]Rock fragments, chert, heavy minerals and bone fragments

PETROGRAPHIC TYPES

Another way to assess the petrology of any sediment is to carefully define and describe the number of petrographic types it contains. In doing so, interest is more effectively focused on the petrographic variability within and between stratigraphic units--information that is totally lost in Table 2.

Eleven petrographic types were recognized using a classification that emphasizes both composition and lamination (Fig. 4). We have also very carefully described these petrographic types in the style of Folk (1960) to help us and others firmly establish the petrographic composition of the Ohio and Chagrin Shale along Lake Erie. Selected photomicrographs show the main textural types (Fig. 5). The average composition of each petrographic type is also given (Table 3).

Claystones: Quartz plus feldspar average 10.4 percent of claystones and range from 6 percent to 16 percent. The quartz is monocrystalline and the feldspar is fresh plagioclase. Modal grain size varies between 0.02 mm and 0.04 mm, medium to coarse silt. Coarsest grain size, defined as the average long diameter of the five largest grains in each sample, averages 0.049 mm, coarse silt, and ranges from 0.017 mm, medium silt, to 0.078 mm, very fine sand. The quartz plus feldspar fraction of claystones is moderately to well sorted. Quartz is very angular to subangular and grains are equant (width to length ratio of 0.90) to elongate (width to length ratio of 0.30). The long axes of quartz grains are oriented parallel to bedding. Quartz is not shape sorted and has both straight and undulose extinction.

Clay minerals average 79.2 percent of claystones, and vary from 54 percent to 91 percent. Clays are white to light green and X-ray diffraction indicates that they are mostly illites and chlorites. Long axes of clay minerals are oriented subparallel to bedding and produce nearly uniform extinction under crossed nicols, except for some clays, which bend around quartz, pyrite, and carbonate and except for small irregular aggregates of clay less than 0.5 mm long which have aggregate polarization of clay minerals but at an angle to bedding.

Claystones contain an average of 2.5 percent mica, and range from a trace amount to 7 percent. Most micas are muscovite with a lesser amount of chlorites and a trace of biotite. Micas are well crystalline with sharp

PERCENT CLAY PLUS MICA

	100–65	65–32	32–0
Unlaminated	Claystone	Mudstone	Unlaminated Siltstone
Laminated	Clayshale	Mudshale	Laminated Siltstone
≥ 15% Organic Material	Bituminous Shale		
≥ 25% Carbonate	Marlstone		Unlaminated Siltstone Unlaminated Siltstone
≥ 15% Pyrite	Pyritic Shale		

FIGURE 4. Definition of shale types. Modified from Potter, *et al.* (1980, Table 1.2)

FIGURE 5 (opposite) Photomicrographs of shale thin sections: A) claystone, B) clayshale, C) mudshale, D) bituminous shale, E) unlaminated siltstone, and F) laminated siltstone.

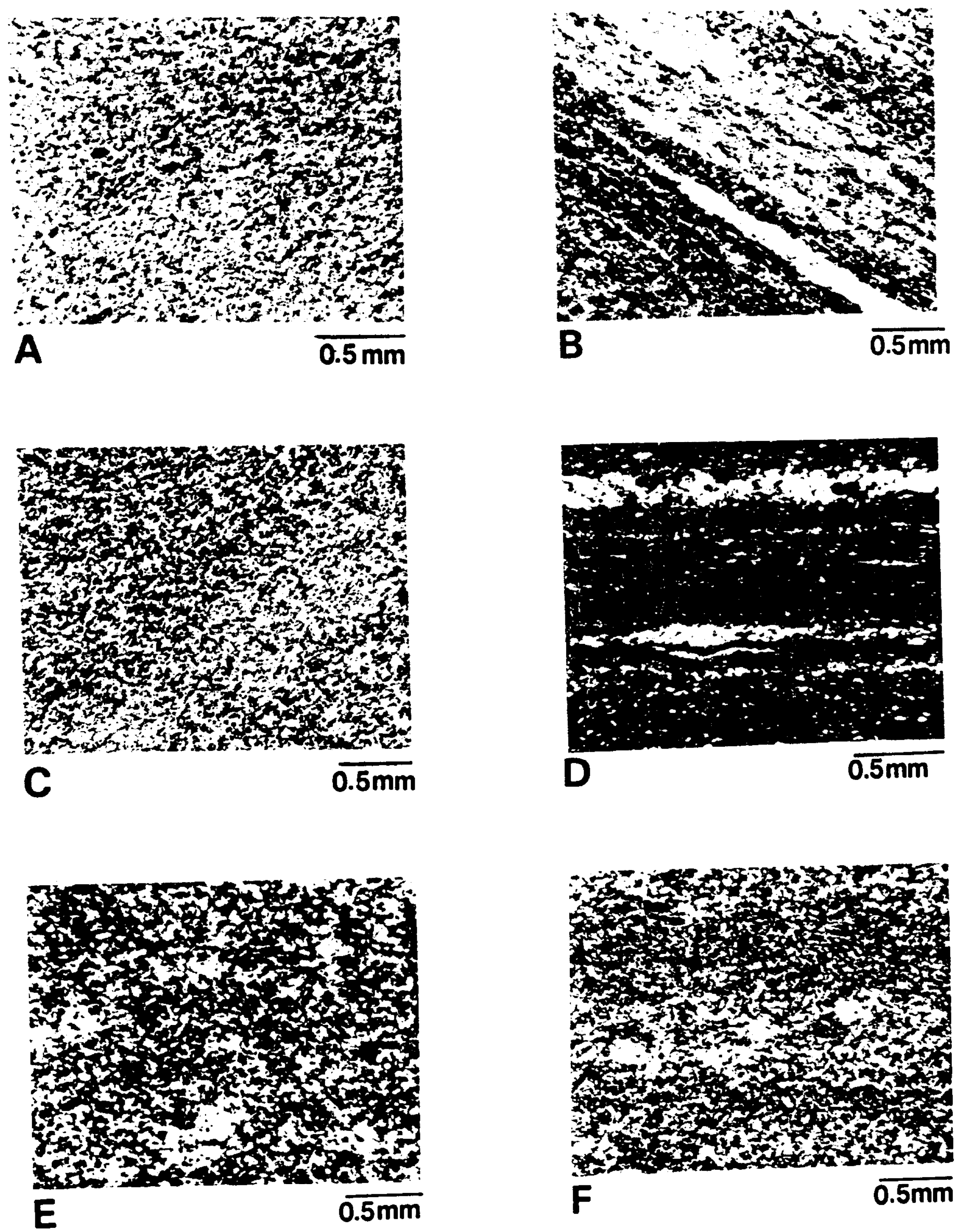
A
0.5 mm
B
0.5mm
C
0.5mm
D
0.5mm
E
0.5mm
F
0.5mm

TABLE 3

AVERAGE COMPOSITION OF SHALE TYPES
(Percent)

	Claystone	Clayshale	Mudshale	Bituminous Shale	Siltstone
COMPOSITION					
Quartz + Feldspar	10.4	13.8	31.2	18.0	68.5
Clay	79.2	71.3	50.2	50.3	6.1
Mica	2.5	2.5	3.5	2.5	3.9
Organics	3.3	5.0	7.2	24.3	T
Tasmanites	T	T	1.0	1.4	-
Pyrite	2.2	4.8	5.0	5.8	T
Carbonate	2.1	2.5	1.5	2.2	19.1
Other	T	T	T	T	1.0
Lamination Types	none	QUARTZ* ORGANIC Clay	QUARTZ ORGANIC	QUARTZ ORGANIC Clay	QUARTZ
Av. Quartz Laminae Thickness (mm)		0.11;	0.32;	0.096;	
Standard Deviation		0.06	0.30	0.07	
Maximum Grain Size	0.049;	0.064;	0.077;	0.071;	0.12;
Size Range (mm)	0.017-0.078	0.034-0.095	0.049-0.108	0.046-0.089	0.075-0.17

*Capital letters indicate dominant laminations grain boundaries. Modal size is about 0.04 mm long and 0.005 mm wide, a width to length ratio of 0.125. A few muscovites are as long as 0.2 mm. The mica fraction of claystones is moderately to well sorted. Most micas are oriented parallel to bedding but a few bend around quartz and are at high angles to bedding.

Claystones average about 3.3 percent organic material and range from containing only a trace amount to 13 percent. Both the black opaque material and the amorphous translucent material are present. Black opaque material is dominant, has generally been partially pyritized, and occurs as equant fragments 0.03 mm to 0.07 mm in diameter to elongate fragments 0.04 mm to 0.1 mm long and 0.01 mm wide. Translucent amorphous material is brown to reddish-brown and occurs as strands (typically less than 0.03 mm long) elongate parallel to bedding.

Tasmanites are rare in claystones and only present in trace amounts, if at all. Most are yellow but some are orange. Individuals are only fragments or have been crushed. *Tasmanites* are poorly preserved in claystones.

Pyrite is ubiquitous in claystones, averages 2.2 percent and ranges from only trace amounts to 6 percent. It occurs as both disseminated anhedral to euhedral crystals 0.01 mm to 0.02 mm in diameter and as larger irregular patches up to 2.5 mm in diameter.

Carbonate minerals are also nearly ubiquitous in claystones, average 2.1 percent, and range from 0 percent to 4 percent. The carbonates occur as disseminated, round to irregular, anhedral crystals, which are typically 0.01 mm to 0.02 mm in diameter. Clays bend around the carbonate crystals, and thus indicate that the carbonate was formed before or during compaction. Claystones probably contain more carbonate than is visible in thin section at 500x, because they contain an average of 7.3 weight percent acid-soluble material, an amount which is three times the average volume percent of 2.1 percent determined from point counts.

Trace amounts of rounded, fine-silt-size zircons are ubiquitous in claystones.

Claystones, by definition, are not laminated. They are internally homogeneous and contain no visible bioturbation structures.

Clayshales: Quartz plus feldspar averages 13.8 percent in all clayshale and ranges from 3 percent to 25 percent; 4.4 percent is concentrated into discrete quartz laminae and the remainder floats in a clay matrix. This mineral fraction is predominantly monocrystalline quartz with both straight and undulose extinction, and minor twinned plagioclase feldspar, which is little altered to clays. Modal grain size of quartz ranges from 0.02 mm to 0.03 mm, medium to coarse silt. Coarsest grain size averages 0.064 mm, very fine sand, and ranges from 0.034 mm, coarse silt, to 0.095 mm, very fine sand. The quartz fraction is moderately to well sorted. Most quartz is subangular to angular, but a few samples have abundant subrounded grains. Grain shape of quartz varies from elongate to equant and the width to length ratio of quartz varies typically from 0.45 to 0.80 in a single sample. Elongate grains are oriented with long axes parallel to lamination. There is no shape-sorting of quartz.

Clay minerals are the major component of clay-shales, average 71.3 percent, and range from 55 percent to 92 percent. Most clays are white; some are light green. X-ray diffraction indicates that they are illites and chlorites. In clayshales with little quartz, clays are uniformly elongate parallel to lamination and have aggregate polarization but in samples with higher quartz content the clay orientation is less uniform, because clays were bent around the more resistant quartz grains during compaction. Clays also bend around and conform to the shape of uncrushed *Tasmanites*.

Micas average 2.5 percent of clayshales and mica abundance ranges from only a trace up to 7 percent. They are well crystallized muscovite and chlorites. Most are 0.01 mm to 0.04 mm long and 0.002 mm to 0.005 mm wide with width to length ratios varying between 0.05 and 0.2. The mica fraction of clayshales is moderately sorted. Most micas are elongate parallel to lamination; some have been bent around quartz grains.

Organic material averages 5.0 percent and ranges from 0 percent to 14 percent of clayshales. Two types of organic material are present: translucent and opaque. The translucent type is brown, brownish-red, or orange amorphous material, which occurs as irregular bodies elongate parallel to lamination; most of this material is less than 0.25 mm long and less than 0.01 mm wide and some of it has been bent around clays and quartz grains. The opaque type of organic material is black, and generally partially pyritized and occurs as elongate to equant strands 0.02 mm to 0.4 mm long and 0.02 mm to 0.03 mm wide; strands are elongate parallel to lamination.

Tasmanites is present not at all or only in trace amounts in clayshales. Rarely, a clayshale may contain as much as 1 percent *Tasmanites*. Most of these spores are yellow; a few are orange in thin section. Most are poorly preserved. Spore walls are 0.0025 mm to 0.01 mm thick. Most individuals are crushed and elongate parallel to lamination; these are 0.05 mm to 0.2 mm long. Some *Tasmanites* are not crushed or only partially crushed and infilled with pyrite. This indicates that the pyrite was precipitated inside the *Tasmanites* both during and before compaction and gave the individual sufficient strength to prevent it from being crushed during compaction of the sediment. Rarely does one find a secondary infilling of chert after pyrite. Uncrushed *Tasmanites* are typically 0.4 mm in diamter.

Pyrite averages 4.8 percent of clayshales with a low of 1 percent and a high of 10 percent. It occurs as both *Tasmanites* infillings and as disseminated crystals. *Tasmanites* infillings are either homogeneous or consist of porous aggregates of pyrite. Disseminated crystals are 0.005 mm to 0.02 mm in diameter and are generally euhedral to subhedral.

Microcrystalline chert occurs in trace amounts as lensoid patches 3 mm long and 0.3 mm wide. These chert lenses are elongate parallel to lamination. Some chert also occurs as small equant patches 0.1 mm in diameter. Chert is present in the shale matrix and usually within 0.5 mm of a quartz lamination. The individual chert crystals are commonly 0.004 mm in diameter. Microcrystalline chert also occurs very rarely as secondary infillings (after pyrite) of *Tasmanites* and also may cement several of the *Tasmanites* together. That it was precipitated syndepositionally or during very early compaction is suggested because as a cement it prevented clays from infiltrating between adjacent individuals.

The average carbonate content of clayshales is 2.5 percent, and ranges from 0 percent to 9 percent. Carbonate occurs as small, equant, anhedral crystals 0.05 mm in diameter disseminated in the shale matrix, and also as small irregular patches in the shale matrix. X-ray diffraction revealed that calcite, dolomite, or siderite can be the carbonate phase in a given sample. The siderite is zoned with dark centers and light-colored edges. It is probable that much carbonate is present which is too small to be seen at 500x because clayshales average 7.3 weight percent acid soluble material (minimum of 3.3 percent and maximum of 10.6 percent), which is presumably mostly carbonate; this is almost triple the average carbonate content of 2.5 percent as determined in thin section.

Two types of lamination are dominant in clayshales: quartz laminae and organic laminae. Of all clayshales, 70 percent contain quartz laminae and 65 percent contain organic laminae; 39 percent of all clayshales contain clay laminae.

Quartz laminae in clayshales are both continuous and discontinuous in approximately equal amounts. Most quartz laminae are ungraded but small fractions are coarse-tail graded and distribution graded. Lamination thickness in clayshales approximates a lognormal distribution (Fig. 12A). Graphic mean quartz lamination thickness is 0.11 mm, median thickness is 0.095 mm, and graphic standard deviation (Folk and Ward, 1957, p. 11-15) is 0.06. In some quartz laminae, carbonate cement (calcite and siderite) has replaced the quartz and locally exceeds 50 percent of the lamination. The quartz grains are elongate to equant and randomly oriented. Grain-to-grain contacts are mostly long and point (Pettijohn, *et al.*, 1972, p. 81) with a lesser amount of concave-convex contacts and only a few sutured contacts. No floating grains exist in the quartz laminae of clayshales.

Organic laminae in clayshales are thin and laterally continuous throughout the width of the thin section. Upper and lower contacts are plane-parallel. Average thickness is 0.15 mm, and thickness ranges from 0.02 mm to 0.36 mm.

Clay laminae in clayshales average 0.38 mm in thickness and range from 0.03 mm to 2.4 mm. The thinner ones are discontinuous lenses and the thicker ones are laterally continuous in thin section. Contacts with the shale matrix are sharp and those of the continuous laminae are planar except for a few which intertongue with the siltier shale matrix.

Mudshales: The quartz plus feldspar fraction averages 31.2 percent of mudshales and ranges from 19 percent to 43 percent; 24.0 percent is concentrated in discrete quartz laminae. Quartz and feldspar is almost all monocrystalline quartz with minor twinned plagioclase and untwinned potash feldspar and a trace of polycrystalline quartz (two crystals per grain). Feldspars are fresh. Grain size of modal quartz is sample dependent and varies between 0.02 mm and 0.03 mm, medium silt. Coarsest grain size averages 0.077 mm, very fine sand, and varies between 0.049 mm, coarse silt, and 0.108 mm, very fine sand. The quartz and feldspar fraction of the mudshales is moderately sorted. Quartz is subangular to angular. Grain shape varies from equant (width to length ratio of 0.95) to elongate (width to length ratio of 0.10). The long axes of elongate grains parallel lamination. There is no shape sorting of quartz. Quartz has both straight and undulose extinction.

Clay minerals in mudshales average 50.2 percent and range from a low of 37 percent and a high of 60 percent. Clays are white to light green and were identified as illites and chlorites by X-ray diffraction. In mudshales with more than 10 percent organic material, the clays are finely intermixed with the organics. Long axes of clay minerals are oriented subparallel to lamination. Clay orientation is not as uniform as in clayshales and claystones, because of the greater quartz content of mudshales disrupts clay mineral orientation.

Micas average 3.5 percent of all mudshales and range from 0 percent to 7 percent. Most mica in mudshales is muscovite but there is some chlorite. The modal grain size of the micas is about 0.05 mm long and 0.005 mm wide and the modal length to width ratio is about 0.10. Long axes of mica flakes are subparallel to lamination, except where they bend around quartz. The mica fraction of mudshales is well sorted.

Organic material averages 7.2 percent of mudshales, and ranges from 1 percent to 13 percent. Amorphous yellow, brown, and reddish-brown translucent material occurs as irregularly shaped strands elongate parallel to lamination which are bent around quartz and micas. These strands are typically 0.03 mm long and 0.01 mm wide. Black opaque organic material is mostly partially pyritized and is present as irregular, elongate and sometimes equant bodies, 0.05 mm to 0.15 mm long and 0.01 mm to 0.02 mm wide. The long dimension of elongate bodies is parallel to lamination.

Mudshales contain an average of 1 percent *Tasmanites*, which range from 0 percent to 2 percent. Most *Tasmanites* are yellow; some are orange. Most have been crushed and are flattened and elongate parallel to lamination, but some were not crushed and were filled with pyrite prior to compaction of the mudshale; others were ripped open before burial and filled with detrital clays and quartz. Crushed individuals are typically 0.2 mm long and 0.02 mm to 0.04 mm wide. Many *Tasmanites* in mudshales are poorly preserved, have jagged outlines, and are partially decayed.

Pyrite averages 5.0 percent of mudshales and ranges from 1 percent to 8 percent. Pyrite occurs dominantly as small (0.04 mm in diameter), irregular disseminated masses of subhedral to euhedral crystals. A lesser amount of pyrite is present as homogeneous infillings of *Tasmanites*.

Mudshales contain an average of 1.5 percent carbonate minerals, which range from 0 percent to 2 percent. The carbonate occurs as irregular cement patches in quartz laminae. Because mudshales contain an average of 7.1 weight percent acid soluble material, more than four times the petrographic volume estimate, it is probable that much carbonate is present which is too small to be seen at 500x with the petrographic microscope.

Microcrystalline chert is rare in mudshales and occurs as small (0.5 mm long and 0.04 mm wide) lenses adjacent and parallel to quartz laminae.

A few mudshales contain a trace of angular phosphatic bone fragments less than 0.1 mm in diameter and small glauconite crystals less than 0.05 mm in diameter.

Trace amounts of rounded fine silt-size zircons are ubiquitous in mudshales.

Mudshales contain abundant laminations. All mudshales in the Ohio and Chagrin Shales along Lake Erie contain quartz laminae. In addition, 83 percent contain organic laminae. Clay laminae are rare in mudshales.

Subequal amounts of the quartz laminae are continuous and discontinuous. Many of the discontinuous quartz laminae are micro-cross laminations. About 50 percent of the quartz laminations in mudshales are ungraded, about 25 percent are coarse-tail graded, and about 25 percent are distribution graded. Quartz lamination thickness in mudshales approximates a lognormal distribution. Mean quartz lamination thickness computed graphically (Folk and Ward, 1957, p. 11-15) is 0.32 mm; median lamination thickness is 0.24 mm and graphic standard deviation is 0.30.

Lamination thickness is irregular within a single lamination. Lower contacts of quartz laminae in mudshales are sharp. Some soles are marked by micro-load casts about 1.0 mm wide and 0.5 mm high. Elongate quartz grains are generally elongate parallel to lamination. There is no shape sorting of quartz within individual laminae. Grain-to-grain contacts are mostly long and point with only a few concave-convex contacts. There are no sutured contacts of floating grains in quartz laminae of mudshales.

Organic laminae in mudshales are thin and laterally continuous and uniform in thin section. Upper and lower contacts are planar and parallel to each other and most contacts are sharp, but a small fraction are gradational. Lamination thickness averages 0.19 mm, ranging from 0.05 mm to 0.43 mm.

Clay laminae of mudshales have an average thickness of 0.15 mm, and range from 0.05 mm thick to 0.35 mm thick. They are discontinuous lenses in thin section and have sharp contacts with the enveloping shale.

Bituminous Shales: Quartz plus feldspar average 14.0 percent of bituminous shales and range from 6 percent to 24 percent; 1.8 percent is concentrated as discrete quartz laminae. Monocrystalline quartz is dominant in this fraction and the feldspar is twinned plagioclase which is present only in trace amounts and shows little alteration to clays. Modal grain size of quartz is between 0.025 mm and 0.03 mm, medium silt. Average coarsest grain size is 0.071 mm, very fine sand, and coarsest grain size ranges from 0.046 mm, coarse silt, to 0.089 mm, very fine sand. The quartz fraction of bituminous shales is moderately sorted. Most grains are very angular to subangular but subrounded grains are abundant although not dominant in a few samples. Quartz grain shape varies from equant (width to length ratio of 0.75) to elongate (width to length ratio of 0.40). Most elongate grains are oriented with their long axis parallel to lamination but there is a small population of randomly oriented grains. Quartz is not shape sorted. Quartz has both straight and undulose extinction.

Clay mineral abundance of bituminous shales averages 50.3 percent with a low of 36 percent and a high of 74 percent. Clays are white to light green and X-ray diffraction indicates that they are illites and chlorites. They are finely intermixed with organic material. Long axes of clay minerals are oriented subparallel to lamination. Clays bend around and conform to the shape of uncrushed *Tasmanites* and quartz grains.

Micas average 2.5 percent of bituminous shales and range from only a trace amount in some bituminous shales to as much as 9 percent in others. Both muscovite and chlorites are present; muscovite is the dominant mica in most samples. Micas are 0.02 mm to 0.02 mm long and 0.0025 mm to 0.033 mm wide with width to length ratios between 0.05 to 0.15. Long axes of most micas are parallel to lamination. The mica fraction of bituminous shales is well sorted.

Bituminous shales contain an average of 24.3 percent organic material but the variability is great so that organic material ranges from 15 percent in some samples to 37 percent in others. Amorphous, brown, reddish-brown, and orange translucent material is usually the most abundant type and is present as elongate strands less than 0.015 mm long and 0.002 mm to 0.003 mm wide which are elongate parallel to lamination. This amorphous material is finely intermixed with, and bent around quartz, clays, and micas. Black opaque organics are subordinate, often partially pyritized, and occur as elongate to equant fragments 0.01 mm to 0.12 mm long and less than 0.01 mm wide. Larger fragments are more elongate than smaller ones and are oriented with the long dimension elongate parallel to lamination.

Tasmanites are more abundant in bituminous shales than in any other type of shale and average 1.4 percent with a low of only a trace and a high of 6 percent. When more abundant than 4 percent they are concentrated in poorly defined zones which parallel bedding. Almost all *Tasmanites* are yellow; a few are orange. Wall widths vary typically between 0.003 mm and 0.005 mm. *Tasmanites* are well preserved in bituminous shales. Most are completely crushed and flattened parallel to lamination and are typically 0.1 mm to 0.15 mm long. Uncrushed individuals are typically 0.3 mm in diameter, and infilled with pyrite. Rarely, *Tasmanites* have been silicified in bituminous shales.

Pyrite is ubiquitous in bituminous shales, with an average abundance of 5.8 percent, a low of 1 percent, and a high of 13 percent. It has three modes of occurrence: homogeneous *Tasmanites* infillings, small disseminated crystals with an average diameter of 0.003 mm, and irregular patches of euhedral crystals 0.02 mm to 0.1 mm long in discrete quartz laminae.

Carbonate minerals average 2.2 percent of bituminous shales, and range from 0 percent to 5 percent. Carbonate occurs as small (0.02 mm to 0.05 mm) anhedral crystals disseminated throughout the rock and as irregular, anhedral, poorly crystalline cement patches in quartz laminae. This carbonate cement has replaced quartz. X-ray diffraction indicates that the carbonate minerals in a given sample may be siderite or calcite. Clay and mica grains are bent around the carbonate crystals.

Chert occurs rarely and only in trace amounts. It is pure and very fine grained (0.0038 mm wide crystals) and occurs in lenses about 0.5 mm long and 0.04 mm wide elongate parallel to lamination. Most of these chert lenses are located within 1 mm of carbonate-cemented quartz laminae, suggesting that a possible source of silica for the chert is the quartz that has been replaced by the carbonate in the quartz laminae.

Heavy minerals are rounded, fine silt-size grains of zircon and rutile and are ubiquitous in trace amounts.

All bituminous shales studied contain laminations. The most abundant type of laminae in bituminous shales are quartz laminae and organic laminae. Quartz laminae occur in 80 percent of all bituminous shales in the Ohio and Chagrin Shales and 64 percent of the bituminous shales contain organic laminae. Twenty percent of the bituminous shales contain clay laminae.

Both continuous and discontinuous quartz laminae occur in bituminous shales. Neither type is dominant, but one type or the other generally prevails in a given sample. All quartz laminations in the bituminous shales are ungraded. Lamination thickness approximates a log-normal distribution. The graphic mean thickness of quartz laminae is 0.096 mm; the graphic median thickness is 0.080 mm, and the graphic standard deviation is 0.07. Contacts of the enclosing quartz laminae with the enclosing shale are sharp and those of the continuous laminae with the enclosing shale are sharp and those of the continuous laminae are planar and parallel to each other. Quartz grains within quartz laminae are elongate to equant; elongate grains are randomly oriented and there is no shape sorting of quartz in the quartz laminae of bituminous shales. Grain-to-grain contacts are mostly long, and point with a lesser amount of concave-convex contacts, rare sutured contacts, and no floating grains. Some quartz laminae contain a few percent carbonate cement which has, in a few samples, replaced quartz.

The organic laminae of bituminous shales have an average thickness of 0.40 mm, but thickness ranges from 0.09 mm to 1.8 mm. They are laterally continuous and uniform in thin section and have plane-parallel upper and lower contacts. Most contacts are sharp; some are gradational.

Clay lamination thickness averages 0.23 mm and ranges from 0.06 mm to 1.08 mm. Clay laminae are laterally continuous in thin section and have sharp, plane-parallel upper and lower contacts.

Laminated and Unlaminated Siltstones: Both are described together, because they are similar in composition and the absence of lamination in almost all siltstones of the Ohio and Chagrin Shales along Lake Erie can be attributed to bioturbation of originally laminated silt or destruction of depositional texture by carbonate replacement. The absence of lamination can be attributed to primary depositional phenomena in only a few siltstone beds; these beds have a basal unlaminated Bouma Ta unit (Bouma, 1962, p. 49) and most of these beds are laminated in the upper parts.

Siltstones contain an average of 68.5 percent quartz and felspar, and range from 30 percent to 89 percent. Both potash feldspar and twinned plagioclase are present in most siltstones, although never in amounts greater than 5 percent. They are almost always somewhat altered to clays. Most quartz is monocrystalline. Only a few grains are polycrystalline and may be composed of as many as 6 crystals. Quartz is angular to very angular but this angularity can be attributed to replacement by carbonate in most samples. Modal quartz size averages 0.048 mm, coarse silt, and ranges from 0.028 mm, medium silt, to 0.065 mm, very fine sand. Coarsest grain size averages 0.12 mm, very fine sand, and ranges from 0.075 mm, very fine sand, to 0.17 mm, fine sand. The quartz fraction of siltstones is generally well sorted. Quartz has both undulose and straight extinction.

Clay minerals average 6.1 percent of siltstone and siltshales, and range from 0 percent to 20 percent. The clays are matrix and are squashed between quartz and feldspars.

Micas average 3.9 percent of siltstones, and range from trace amounts to 12 percent. Micas are mostly muscovite with minor chlorite. Some samples contain a trace of biotite. Some muscovites occur as small radiating books, indicating that some micas are diagenetic. Modal grains size is 0.1 mm long x 0.02 mm wide (width to length ratio of 0.2).

Red translucent amorphous organic material averages trace amounts in siltstones, and ranges from 0 percent to 1.0 percent. Fragments of organic material are irregular and elongate and less than 0.1 mm long.

The average carbonate content of siltstones is 19.1 percent, and ranges from 0 percent to 67 percent. Carbonate is a cement and calcite, dolomite, and siderite all occur. All of these minerals replace quartz, sometimes extensively. Calcite cement is anhedral and forms blocky and poikiltic crystals. Dolomite and siderite are anhedral to euhedral and crystal faces cut quartz grains. Pyrite is ubiquitous, although it is rarely as much as 2 percent of some samples. It is commonly 0.06 mm in diameter.

In some siltstones, calcite and siderite have preferentially replaced alternate quartz laminae.

The following other components occur in siltstones as coarse to fine silt and are never more than 1 percent detrital chert, detrital zircon, and tourmaline, hematite and several types of rock fragments: granitic (containing quartz and plagioclase), argillaceous siltstone and fine-grained quartz mica schists.

Siltstones and siltshales which contain abundant clays are poorly sorted; those with only a little clay are well sorted. In samples with less than 5 percent carbonate cement, grain-to-grain contacts are mostly tangential and point with a lesser amount of concave-convex contacts and almost no floating grains or sutured contacts. In samples with more than 50 percent carbonate cement, most grains are floating in poikilitic cement.

Lamination and cross-lamination in siltstones consists mostly of alternating layers made of quartz and clay and mica, mostly quartz. Many laminae exhibit coarse-tail grading and some have distribution grading. In many cases, the entire specimen as well as the individual quartz laminae are graded, with each successive lamination (in the upward direction) containing slightly finer quartz than the one below it.

Marlstones: Marlstones contain more than 25 percent carbonate minerals and are unlaminated. The carbonates in a given sample may be calcite, dolomite, or siderite. Carbonate occurs as anhedral to subhedral crystals 0.02 mm to 0.05 mm in diameter. Clays and micas in marlstones have uniform orientation parallel to bedding and are not bent around the carbonate crystals, indicating that the carbonate was formed after compaction.

A minor petrofacies, the marlstones, besides having more than 25 percent carbonate, have the attributes of claystones.

Sandstones: The only sandstones seen were from core K-8191 B-2 of Herron Testing Labs (locality 9, Fig. 1). A brief description of a typical sample follows. Composition was estimated with visual comparator charts (Table 4).

The sandstones are very fine-grained, very poorly sorted, angular, texturally immature feldspathic graywackes (Dott, 1964, Fig. 3).

The modal grain size of framework grains is 0.065 mm, very fine sand, and coarsest grain size is 1.7 mm, very coarse sand. Sorting is very poor and grains are angular. Grain-to-grain contacts are mostly long, point and floating; only a few are concave-convex and none are sutured.

The average composition of the framework is $Q_{81}F_{17}Rf_{2}$.

PETROGRAPHY OF STRATIGRAPHIC UNITS

Estimates of the abundance of petrographic types for the different stratigraphic units are especially difficult to obtain, when only parts of the different stratigraphic units are cored, as is mainly true of the Devonian shales along Lake Erie. We simply averaged results from available cores (Table 5) and made no attempt to weight the results, by thickness or volume. Compositional variations within units, as seen on graphic petrographic plots, are also discussed and related to gamma ray logs, wherever possible.

The lower part of the Huron Member of the Ohio Shale contains the greatest amount of bituminous shale of any stratigraphic unit of the Ohio and Chagrin Shales along Lake Erie. In general, vertical profiles of composition of the lower part of the Huron Member of the Ohio Shale show an upward increase in the clay and mica and an accompanying de-

TABLE 4

ESTIMATED COMPOSITION OF SANDSTONE

Component	Modal Abundance	Comments
Quartz	49	Mostly monocrystalline, a few polycrystalline grains (6 crystals per grain). Equant to elongate. Ninety percent of quartz has undulose extinction; 10 percent has straight extinction.
Clay	25	Fine-grained clay matrix.
Feldspar	10	Potash feldspar and twinned plagioclase. Fresh to extremely weathered.
Organics	10	Translucent brown material finely intermixed with clays.
Mica	5	Mostly muscovite, some biotite and chlorite in distinct crystals and small books.
Rock Fragments	1	Fine-grained quartz mica schists and elongate, imbricated rip-up clasts of bituminous shale 1.7 mm long and 0.4 mm wide. Some small silt-size rounded chert fragments.
Pyrite	T	Very fine disseminated pyrite less than 0.02 mm in diameter.

TABLE 5

ABUNDANCE OF PETROGRAPHIC TYPES IN EACH STRATIGRAPHIC UNIT

Stratigraphic Unit and Samples	Petrographic Types
Ohio Shale	
Cleveland Member, 6	BITUMINOUS SHALE,* Siltstone
Three Lick Bed, 21	CLAYSTONE, CLAYSHALE, Mudstone and Siltstone
Upper part of Huron Member, 11	CLAYSHALE, BITUMINOUS SHALE, Claystone
Middle part of Huron Member, 10	BITUMINOUS SHALE, Mudstone, Claystone
Lower part of Huron Member, 22	BITUMINOUS SHALE, Clayshale
Chagrin Shale, 22	CLAYSHALE, Siltstone, Claystone

*Capital letters indicate dominant lithology crease in organics from the base to the middle of the unit and then an opposite trend upward (Fig. 6). The quartz-plus-feldspar fraction remains constant throughout. These compositional variations are seen on gamma-ray logs as a decrease in radioactivity near the middle of the unit. Coarsest grain size in the lower part of the Huron Member has no vertical or lateral trends and its values vary irregularly between 0.05 mm and 0.10 mm.

Bituminous shale also predominates in the middle part of the Huron Member of the Ohio Shale although this part of the Huron contains a greater percentage of marlstone than any other stratigraphic unit.

The upper part of the Huron Member contains only a moderate percentage of bituminous shale, but most of its clayshales and claystones, which predominate, are organic-rich, and account for its dark-gray color.

The Three Lick Bed of the Ohio Shale consists of dark-gray claystones and clayshales in about equal amounts. In the Three Lick Bed, siltstone, siltshale, and mudshale are also present in Cuyahoga County, but to the west in Lorain and Erie Counties, claystone and clayshale are predominant. Many of the siltstones, siltshales, and mudshales in the Three Lick Bed have been cemented and partially replaced by calcite and/or siderite.

Together, the middle and upper parts of the Huron Member and the Three Lick Bed of the Ohio Shale exhibit a steady upward increase in the clay-plus-mica and quartz-plus-feldspar fractions and an accompanying upward decrease of the organic fraction of the shales (Fig. 7). There is also a somewhat irregular upward decrease of coarsest grain size in these stratigraphic units (Fig. 6). Coarsest grain size varies between 0.05 mm and 0.09 mm at the base of the middle part of the Huron Member and decreases to between 0.03 mm and 0.07 mm at the top of the Three Lick Bed.

Petrographically, the Cleveland Member of the Ohio Shale everywhere contains black bituminous shale and dark-gray to medium-gray clayshale. Siltstones, siltshales, and black very fine-grained sandstones are present east of the City of Cleveland, and there only in the lower two-thirds of the Cleveland Member. Siltstone is also locally abundant west of Cleveland at Lakewood, Ohio, along the Rocky River.

The Chagrin Shale is composed mostly of clayshale and contains minor claystone and mudshale, and only a few percent siltstone and siltshale. Carbonate is rare. The Chagrin Shale has a general but irregular upward increase in the quartz plus feldspar fraction (Fig. 8). Coarsest grain size has no overall vertical trend and varies irregularly between 0.04 mm and 0.09 mm.

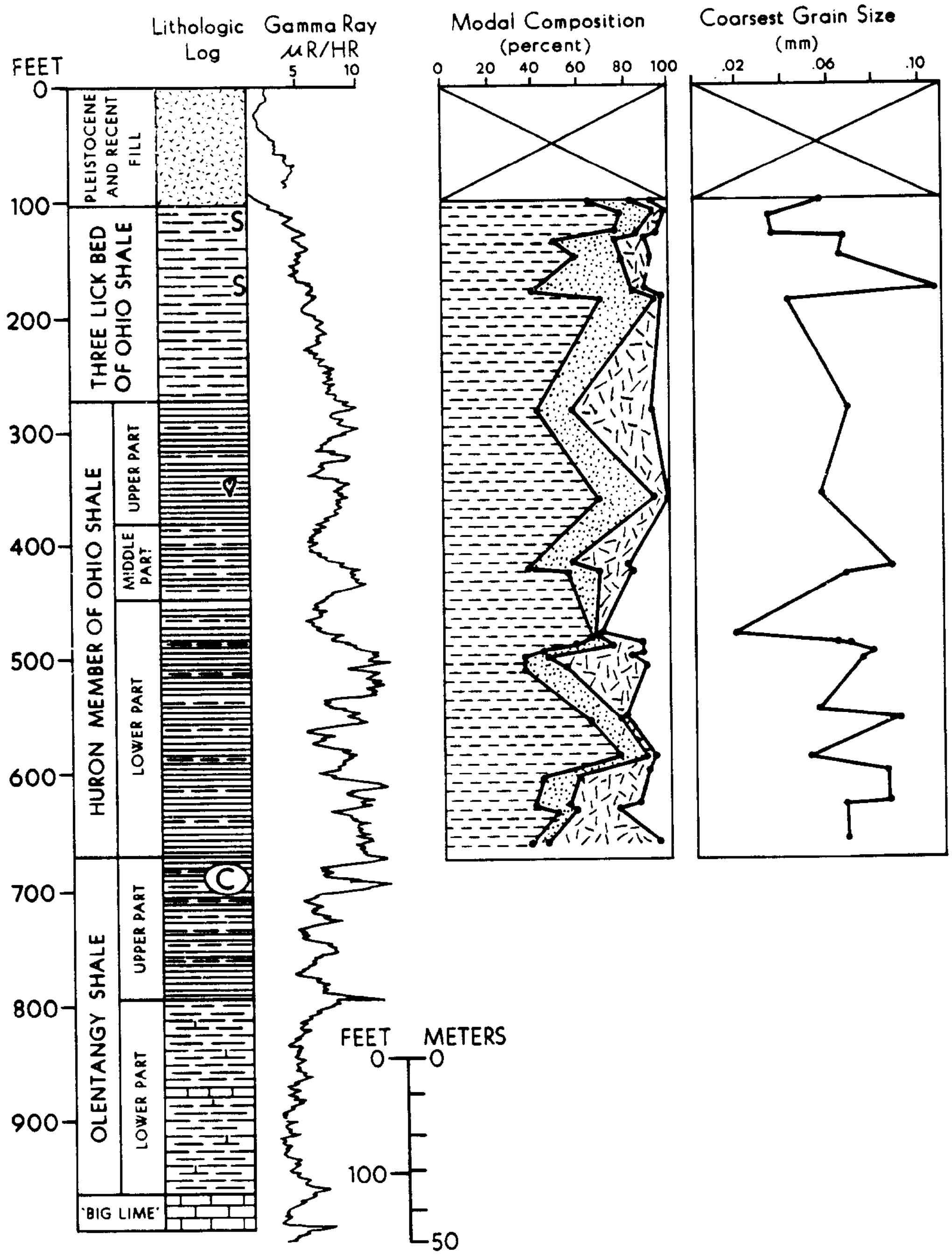

Figure 6. Lithologic column, gamma-ray borehole log, and petrologic profile of the Cleveland No. 1 (Whiskey Island) drill hole International Salt Co. (locality 8, Figure 1).

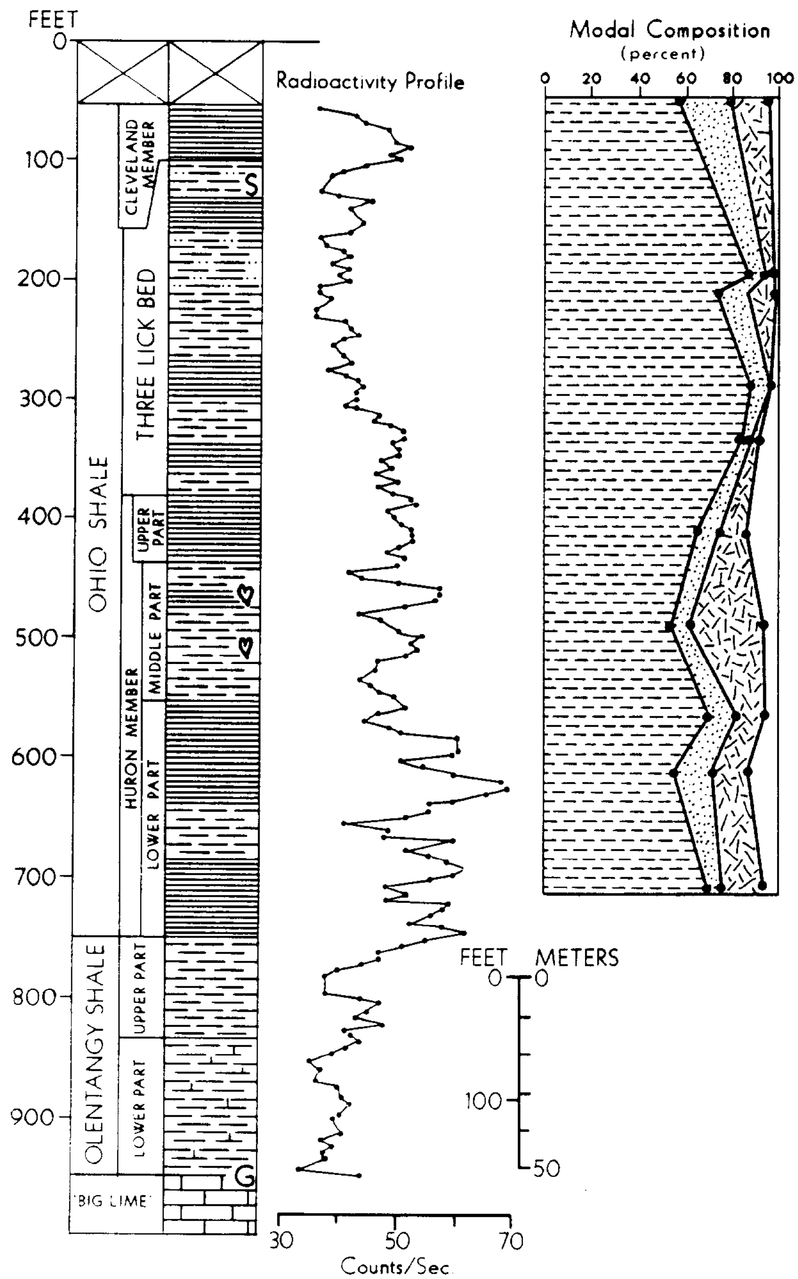

Figure 7. Lithologic, radioactivity and petrologic profiles of the Avon drill hole No. 3 of the International Salt Co. (locality 6, Figure 1).

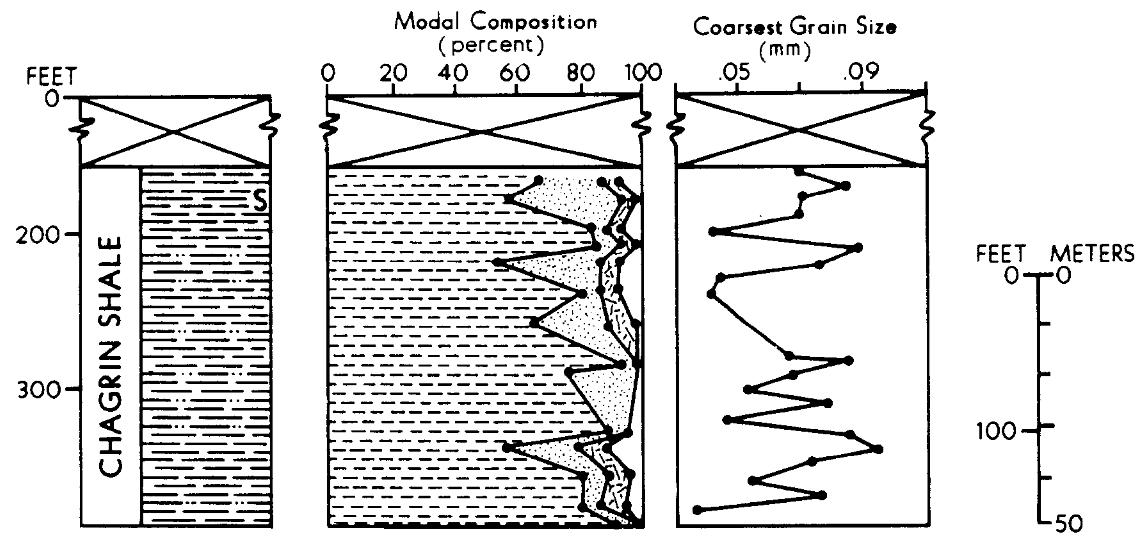

Figure 8. Lithologic and petrologic profiles of drill hole TX-7, Perry Nuclear Power Plant (locality 13, Figure 1).

LAMINATION

We think lamination is an important variable in shale petrology, especially for production of gas. Degree and kind of lamination is directly relevant to the gas potential of a shale because a laminated shale can be expected to deliver more gas than one completely bioturbated, given comparable maturation and kerogen content. Thus any study of a gas reservoir in shale should give high priority to the nature and distribution of the laminations. Good lamination has also been taken to mean that bottom conditions were unfavorable to burrowing or crawling organisms (Hallam, 1967; Byers, 1977) and thus, as a first approximation, lamination or its absence can be linked to the degree of oxygenation of bottom waters. In addition, the kind of lamination, and its associated microsedimentary structures should be directly relatable to depositional processes, which vary with different muddy environments (Reineck, 1974), although information is still scant for most shales.

Regardless of composition, laminae are best described by their thickness, nature of contacts with the surrounding rock, lateral continuity, cementation, porosity, and, for quartz laminae, type of grading. Quartz laminae may be ungraded, coarse-tail graded, or distribution graded (Middleton, 1967, p. 487). Graded quartz laminae may indicate deposition from suspension currents whereas ungraded laminae may more commonly represent deposition from traction. Three basic types of lamination occur in the Ohio and Chagrin Shales along Lake Erie: clay laminae, organic laminae, and quartz laminae (Table 6). Quartz and organic laminae occur together more often than any other combination of lamination types and have a Jaccard correlation coefficient (Till, 1974, p. 135; Cheatham and Hazel, 1969, p. 1131-1332) of 0.54 whereas quartz and clay laminae and organic and clay laminae have low values, 0.21 and 0.13, respectively, indicating that the clay laminae do not commonly occur with either quartz laminae or organic laminae.

The thickness of individual siltstone laminae in laminated shale types was carefully counted and proved to be more informative (Table 7 and Figure 9) for evaluation of the gas potential of the Ohio Shale along Lake Erie.

The different measures of central tendency--graphic mean, 50th percentile and phi mean--all vary in the same manner and the Chagrin has the greatest average value. The Three Lick Bed has an intermediate value (but one that is close to that of the Huron) and the average for the Huron is the smallest. Scheffee's test of all contrasts (Scheffee, 1953; Horberg and Potter, 1955, p. 21-22) supports this conclusion--the null hypothesis of no difference between all three pairs of means was rejected at 0.05 significance level (although barely so when the

TABLE 6

LAMINAE: TYPES AND OCCURRENCE

Part A: Definitions

Clay Laminae: More than 95 percent clay minerals, oriented in plane of lamination, aggregate polarization; sharp contacts with surrounding shale; rare to common.

Organic Laminae: Quartz + clay + organics, more organics than surrounding shale; most contacts with surrounding shale sharp, some gradational; common to abundant.

Quartz Laminae: More than 75 percent silt-size quartz grains; most grain-to-grain contacts long and point; carbonate cements some laminae, locally replaces quartz extensively; subdivided according to type of grain-size grading.

Ungraded: No grain-size variation in vertical direction.

Coarse-tail graded: Quartz content and grain-size decreases vertically within the lamination with an increase in clays; grading mostly normal, some reverse.

Distribution graded: Quartz size decreases upward within the lamination.

Part B: Relations to Shale Types

	Quartz Laminae	Organic Laminae	Clay Laminae
Clayshale	70	65	39*
Mudshale	100	83	0*
Bituminous Shale	80	64	20*

* Percentages of lamination types in petrographic type sum to more than 100 percent because different types of laminae can be seen in the same thin section

TABLE 7

THICKNESS OF LAMINAE IN DEVONIAN SHALES

Part A: Frequency Distributions

Class Interval (mm)	Huron Mbr.			Three Lick Bed			Chagrin Shale		
	Number	%	Σ%*	Number	%	Σ%	Number	%	Σ%
0.01-0.02	0	0	0	0	0	0	0	0	0
0.03-0.04	4	10.3	10.3	1	5	5	1	3.8	3.8
0.05-0.08	19	47.6	58.8	5	25	30	2	7.6	11.4
0.09-0.16	11	28.3	86.9	10	50	80	3	11.5	22.9
0.17-0.32	3	7.9	94.8	3	15	95	7	27.1	50.0
0.33-0.64	1	2.6	97.4	1	5	100	4	15.3	65.3
0.65-1.28	1	2.6	100	0	0	100	7	27.1	92.4
1.29-2.56	0	0	100	0	0	100	2	7.6	100
	39		100	20		100	26		100

Part B: Statistical Summary

	Huron Mbr.	Three Lick Bed	Chagrin Shale
Graphic Mean (mm)	0.090	0.120	0.50
50th Percentile (mm)	0.078	0.110	0.34
ϕ mean (phi units)	2.988	2.721	0.973
ϕ Standard Deviation (phi units)	2.544	2.125	2.551

*Cumulative percent

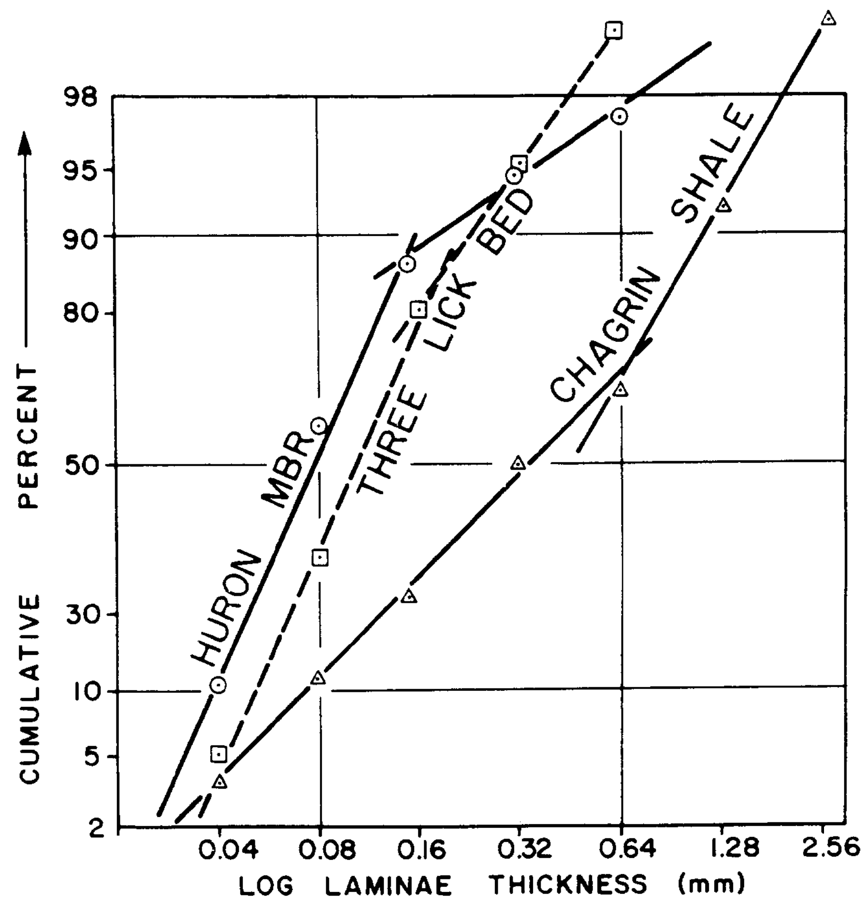

Figure 9. Cumulative curves of laminae thickness plotted on logarithmic probability paper. Curves based on 39 (Huron Mbr.), 20 (Three Lick Bed) and 20 (Chagrin Shale) observations.

sample means of the Three Lick Bed and the Huron Member were tested.

GEOCHEMISTRY: ORGANIC CARBON, HYDROGEN AND NITROGEN

We assessed the gas potential of the Devonian shales primarily by analyses of hydrogen, carbon and nitrogen. The ratio of hydrogen to carbon has been widely used as an indicator of thermal maturity of organic matter and the ratio of nitrogen to carbon has been used to infer the source of the organic matter. However, in shales all three of these elements occur in minerals as well as in organic matter and therefore their contribution must be evaluated.

Thirty-two shale samples were analyzed for organic carbon, whole-rock hydrogen, and whole-rock nitrogen (Table 8) with a Perkin-Elmer 240 Elemental Analyzer. Samples were ground and treated with acid to remove mineral carbon. The insoluble residues were then placed inside a capsule in the Elemental Analyzer and combusted. The resulting gases are analyzed for weight percent carbon, hydrogen, and nitrogen and these values are then corrected for weight loss during acid treatment.

Percent carbon is equivalent to percent organic carbon because mineral carbon was removed by acid solution. The hydrogen is a whole rock value and is present as organic hydrogen and an inorganic hydrogen in clays. Nitrogen is also a whole rock value and is probably mostly inorganic because it does not vary with organic carbon.

The shales of the Ohio and Chagrin Shales along Lake Erie contain an average of 0.42 weight percent inorganic hydrogen present in clay minerals. This estimate was calculated by plotting whole rock hydrogen vs. organic carbon and performing simple linear regression (Potter _et al_., 1979; Fig. 10, this paper). The intercept at zero carbon is 0.42 weight percent, the average amount of inorganic hydrogen present in the shales. The slope of the line is 0.079, which is the average weight ratio of organic hydrogen to organic carbon, and converts to an atomic H/C ratio of 0.94.

The average value of 0.42 weight percent inorganic hydrogen is typical of Upper Devonian shales of the Appalachian basin (Potter _et al_., 1980, p. 49). The atomic H/C ratio of 0.94 is typical of Upper Devonian shales in Ohio but decreases eastward to about 0.4 in central West Virginia because of increasing paleotemperature. The higher paleotemperatures in West Virginia caused the organic matter to be more thermally mature there than in Ohio (Potter _et al_., 1980, p. 56).

Average percentages of organic carbon, whole-rock hydrogen, and whole-rock nitrogen were calculated for each stratigraphic unit as was the average percent of organic carbon in the bituminous shales of each stratigraphic unit (Table 9). The trivariate means of organic carbon, hydrogen, and nitorgen were plotted for each stratigraphic unit, as was the polygon depicting the 90-percent confidence limits for each mean (Fig. 11). In plots of this type, two sample sets are considered as two distinct geochemical facies if the confidence polygons for the sets do not overlap or only slightly overlap; if the confidence polygons for the two sample sets overlap, then they belong to the same geochemical facies.

TABLE 8

ORGANIC CARBON, WHOLE-ROCK HYDROGEN, AND WHOLE-ROCK NITROGEN VALUES OF THE OHIO AND CHAGRIN SHALES ALONG LAKE ERIE

Drill Hole	Sample Depth (feet)	Stratigraphic Unit	Organic Carbon (weight %)	Whole-Rock Hydrogen (weight %)	Whole-Rock Hydrogen (weight %)
Drill hole B-19	19.8	Three Lick Bed[1]	4.09	0.76	0.13
Erie County Nuclear	30.1	Three Lick Bed[1]	0.31	0.59	0.08
Power Plant	70.8	Upper part of Huron Mbr[1]	5.46	0.89	0.16
(locality 3, Fig. 1)	118.1	Upper part of Huron Mbr[1]	0.76	0.49	0.04
	153.7	Middle part of Huron Mbr[1]	0.54	0.55	0.07
	167.3	Middle part of Huron Mbr[1]	4.18	0.60	0.06
	254.5	Lower part of Huron Mbr[1]	7.15	0.87	0.18
	265.2	Lower part of Huron Mbr[1]	5.95	0.90	0.12
Drill hole K-6268 B-1	11.0	Cleveland Mbr[1]	4.80	0.76	0.18
Herron Testing Labs	29.0	Cleveland Mbr[1]	5.82	0.87	0.24
(locality 5, Fig. 1)					
Avon hole No. 3	53.3	Cleveland Mbr[1]	4.09	0.59	0.19
International Salt Co.	178.1	Three Lick Bed[1]	0.35	0.66	0.06
(locality 6, Fig. 1)	258.0	Three Lick Bed[1]	2.18	0.79	0.13
	318.1	Upper part of Huron Mbr[1]	3.83	0.76	0.16
	451.8	Upper part of Huron Mbr[1]	3.71	0.64	0.14
	637.8	Lower part of Huron Mbr[1]	4.17	0.82	0.18
	657.7	Lower part of Huron Mbr[1]	0.13	0.49	0.09
Cleveland hole No. 1	101.5	Three Lick Bed[1]	0.87	0.57	0.09
(Whiskey Island)	116.0	Three Lick Bed[1]	0.54	0.64	0.11
International Salt Co.	285.0	Upper part of Huron Mbr[1]	6.55	0.93	0.19
(locality 8, Fig. 1)	350.0	Upper part of Huron Mbr[1]	2.99	0.74	0.18
	391.0	Middle part of Huron Mbr[1]	0.28	0.46	0.14
	422.0	Middle part of Huron Mbr[1]	5.69	0.95	0.20
	500.0	Lower part of Huron Mbr[1]	8.87	1.10	0.26
	662.0	Lower part of Huron Mbr[1]	6.70	1.07	0.28
Drill hole K-8191 B-2	17.0	Cleveland Mbr[1]	3.69	0.81	0.12
Herron Testing Labs	31.0	Chagrin Shale	0.77	0.37	0.06
(locality 9, Fig. 1)					
Drill hole TX-7	200.1	Chagrin Shale	0.32	0.62	0.11
Perry Nuclear Power Plant	360.0	Chagrin Shale	0.43	0.56	0.11
(locality 13, Fig. 1)					
Gerald hole No. 1	980.0	Lower part of Huron Mbr[1]	1.70	0.46	0.00
International Salt Co.	1020.0	Lower part of Huron Mbr[1]	2.11	0.66	0.00
(locality 16, Fig. 1)	1060.0	Lower part of Huron Mbr[1]	5.05	0.69	0.03

[1] Of Ohio Shale

TABLE 9

ORGANIC CHEMISTRY AND SOURCE-ROCK EVALUATION
(Means and Standard Deviations)

	Organic carbon (weight %)	Hydrogen (weight %)	Nitrogen (weight %)	Organic carbon in bituminous shales (weight %)	Source-rock evaluation[1]
Ohio Shale					
Cleveland Member[2]	4.60±1.09	0.76±0.14	0.18±0.06	4.06±1.09	excellent
Three Lick Bed[2]	1.39±1.23	0.67±0.07	0.10±0.02	0[3]	good
Upper part of Huron Member[2]	3.88±1.35	0.74±0.14	0.14±0.05	6.01±3.44	excellent
Middle part of Huron Member[2]	2.67±3.16	0.64±0.25	0.12±0.08	4.94±4.77	excellent
Lower part of Huron Member[2]	4.65±1.78	0.76±0.16	0.13±0.07	7.17±1.46	excellent
Chagrin Shale	0.51±0.40	0.52±0.23	0.09±0.05	0[3]	poor

[1]Rated by percent organic carbon (Thomas, 1979, p. 1096)

[2]Of Ohio Shale

[3]Unit does not contain bituminous shales

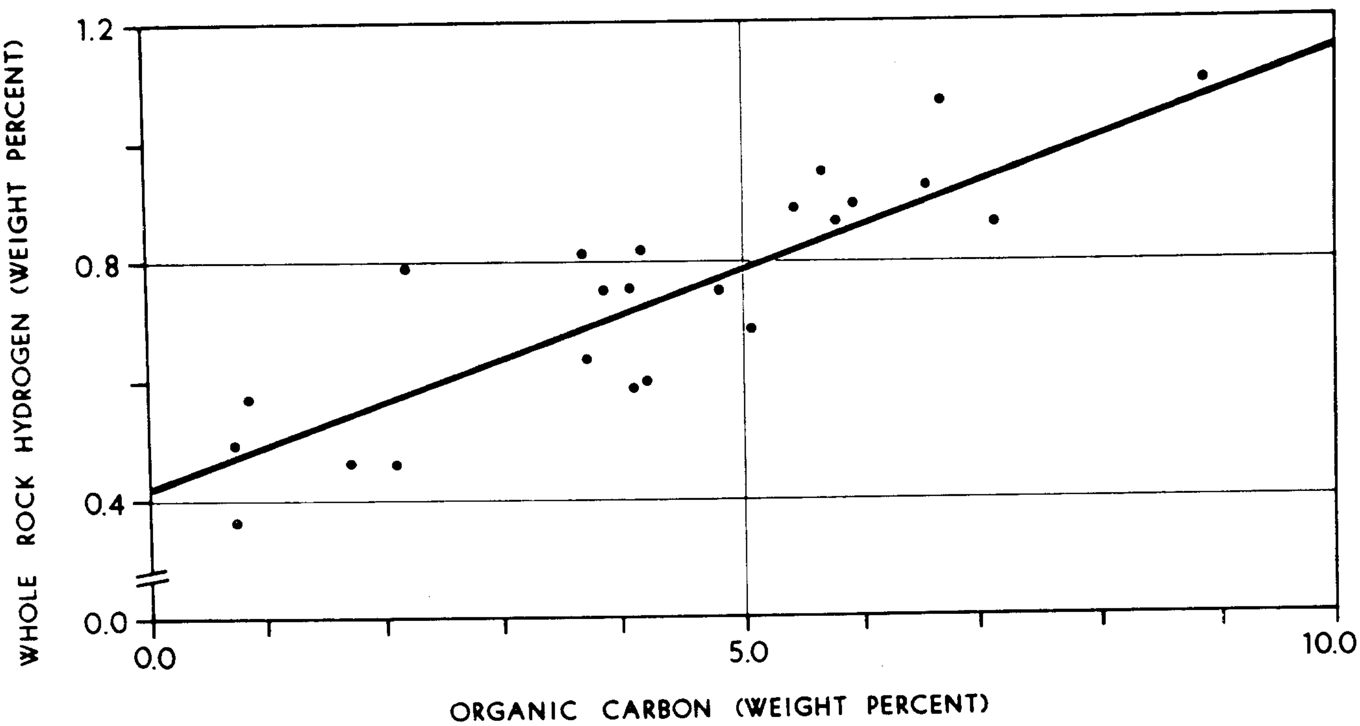

Figure 10. Linear regression of whole-rock hydrogen and organic carbon.

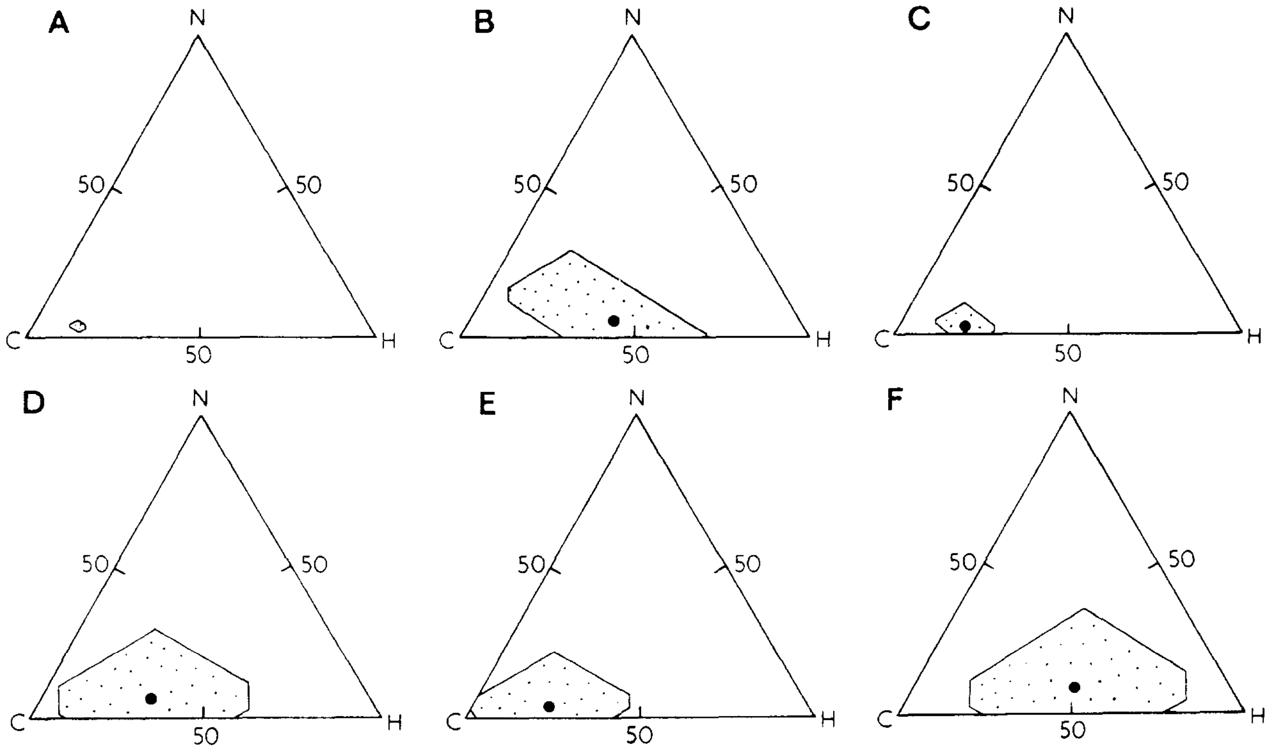

Figure 11. Trivariate means and 90 percent confidence polygons of hydrogen, nitrogen, and organic carbon: A) Cleveland Member, B) Three Lick Bed, C)upper part of Huron Member, D) middle part of Huron Member, E) lower part of Huron Member, and F) Chagrin Shale.

The data indicate that two geochemical facies exist in the Ohio and Chagrin Shales along Lake Erie; a carbon-rich facies and a hydrogen-rich facies. The carbon-rich facies is represented by the dark-gray to black shales of the Cleveland Member and upper and lower parts of the Huron Member of the Ohio Shale. The hydrogen-rich facies is represented by the gray shales of the Chagrin Shale. The interbedded dark-gray and medium-gray shales of the Three Lick Bed and middle part of the Huron Member represent a transition between these two facies.

Percentage of organic carbon was used to evaluate the source rock potential of each stratigraphic unit according to values given by Thomas (1979, p. 1096; Table 9, this paper). The average bituminous shale from each stratigraphic units was also evaluated, and all are excellent potential source rocks.

GAS POTENTIAL

Gas shows are most abundant along Lake Erie in the Chagrin and Three Lick Bed of the Ohio Shale (Fig. 3 and Tables 5 and 10). The much greater thickness of siltstone laminae in the shales of the Chagrin and more siltstone beds seem responsible for its gas shows. The abundance of shows in the Three Lick Bed is more difficult to explain, because its laminae are thinner although some siltstone beds are present and may be the chief explanation.

Gas shows are not primarily dependent on source-rock evaluation because they are concentrated in the two stratigraphic units which have the lowest source rock evaluations, the Three Lick Bed of the Ohio Shale and the Chagrin Shale.

Thermal maturity of organic matter does not control gas distribution because the concentrations of gas shows are unrelated to present burial depth. Thermal maturity of organic matter does control the total amount of gas present in the shales, however (Tissot _et al_., 1974; Hood _et al_., 1975, p. 986, 991-994).

Cementation patterns of quartz laminae do not control the distribution of gas shows as far as we presently know. More quartz laminae and siltstones in the Three Lick Bed and Chagrin Shale are cemented and replaced by carbonate than in any of the other stratigraphic units. In spite of this regional cementation the Three Lick Bed and the Chagrin Shale have the most gas shows. Perhaps because many of their quartz laminae remain uncemented.

What are the source rocks for this gas and how does the gas get from the source rocks to the reservoirs? The source rocks may be located either in the same stratigraphic units, or in idfferent stratigraphic units than the reservoirs, the latter indicating extensive hydrocarbon migration.

TABLE 10

SOURCE ROCK AND RESERVOIR CHARACTERISTICS
OF THE OHIO AND CHAGRIN SHALES

Stratigraphic Unit	Gas Shows	Source-Rock Evaluation[1]	Dominant Petrographic Type (see Table 5)	Laminated Shale (%)	Mud-Shale & Siltstone (%)	Amount of Cemented Quartz Laminae & Siltstones
Ohio Shale						
Cleveland Mbr	Sparse	Excellent	Bituminous sh. & siltstone	84	19	Some
Three Lick Bed	Abundant	Good	Clayshale & siltstone	58	23	Much
Upper part of Huron Mbr	Sparse	Excellent	Clayshale & bituminous sh.	56	0	Some
Middle part of Huron Mbr	Sparse	Excellent	Bituminous sh.	62	0	Some
Lower part of Huron Mbr	Sparse	Excellent	Bituminous sh.	82	0	Some
Chagrin Shale	Abundant	Poor	Clayshale & siltstone	77	23	Some

[1] Rated by percent organic carbon (Thomas, 1979, p. 1096)

The Three Lick Bed of the Ohio Shale has a good source rock evaluation (Table 10), which should enable it to be both a good source rock and a good reservoir. The Chagrin Shale, however, has a poor source-rock rating and the hydrocarbons probably migrated into the Chagrin Shale from better source rocks: the upper, middle, and/or lower parts of the Huron Member of the Ohio Shale.

EVALUATION

This study shows the difficulties of relating petrology to the distribution of gas shows in a shale sequence--when the gas shows come from one data source, drillers' logs, and the petrology is based on scattered cores and outcrops, none of which had gas shows. Consequently it is difficult to explicitly relate the one to the other. Perhaps the combination of geophysical logs combined with sidewall cores from zones with gas shows would be better.

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APPENDIX

PETROLOGY AND PETROGRAPHIC TYPES OF DEVONIAN SHALE ALONG LAKE ERIE

Part A. Counted Samples

Stratigraphic Unit	Depth (Feet)	Rock Name	Quartz + Feldspar	Clay	Mica	Organics	*Tasmanites*	Pyrite	Carbonate	Other[1]
		Drill Hole B-19, Erie County Nuclear Power Plant, Erie County, Ohio								
TLM[2]	11.1	Clayshale	9	67	3	10	T	7	3	1
TLM	19.8	Claystone	12	75	1	6	T	3	3	–
UPHM[3]	60.1	Clayshale	16	61	3	8	1	2	9	–
UPHM	90.2	Bituminous Shale	10	68	T	18	1	2	1	T
UPHM	118.1	Pyritic Shale	9	63	5	7	T	16	T	–
MPHM[4]	167.3	Bituminous Shale	6	47	2	26	1	7	11	–
LPHM[5]	205.2	Bituminous Shale	18	43	9	20	T	5	4	1
LPHM	218.3	Clayshale	8	71	5	8	1	4	3	–
LPHM	227.4	Bituminous Shale	13	54	4	18	2	6	3	–
LPHM	254.5	Bituminous Shale	13	58	4	17	T	7	1	T
LPHM	265.2	Bituminous Shale	24	40	4	15	6	9	2	–
		Drill Hole K-6268 B-1, Herron Testing Labs, Lorain County, Ohio								
CM[6]	11.0	Bituminous Shale	6	74	1	17	1	1	–	–
CM	20.0	Pyritic Shale	7	57	1	6	T	27	2	–
CM	29.0	Bituminous Shale	7	64	3	23	1	2	–	–
		Avon Drill Hole No. 3, International Salt Company, Lorain County, Ohio								
CM	53.3	Bituminous Shale	24	55	2	17	T	2	T	–
TLM	158.4	Siltshale	30	–	T	6	T	1	68	T

Appendix - Part A

Stratigraphic Unit	Depth (Feet)	Rock Name	Quartz + Feldspar	Clay	Mica	Organics	Tasmanites	Pyrite	Carbonate	Other
TLM	158.4	Marlstone	24	7	10	T	-	-	58	1
TLM	200.0	Claystone	9	85	3	2	-	1	-	-
TLM	217.8	Claystone	13	69	4	13	T	1	-	-
TLM	298.0	Claystone	9	86	4	1	-	T	-	-
TLM	338.4	Clayshale	4	82	3	3	T	7	1	-
UPHM	419.0	Clayshale	9	66	1	12	1	2	9	-
MPHM	496.9	Bituminous Shale	8	53	2	33	T	3	1	-
LPHM	568.1	Clayshale	11	67	2	14	-	4	2	-
LPHM	618.0	Bituminous Shale	13	55	5	16	T	6	5	-
LPHM	717.6	Bituminous Shale	7	69	2	19	T	3	-	T
Cleveland Drill Hole No. 1 (Whiskey Island), International Salt Company, Cuyahoga County, Ohio										
TLM	101.5	Clayshale	21	62	2	7	1	7	-	-
TLM	116.0	Clayshale	18	76	2	3	-	1	-	-
TLM	130.5	Clayshale	11	75	1	7	-	6	-	-
TLM	138.3	Mudshale	28	47	2	13	2	8	-	-
TLM	151.0	Mudshale	19	60	-	13	2	6	-	-
TLM	180.0	Mudshale	43	37	3	7	2	8	-	-
TLM	188.5	Clayshale	26	67	2	1	-	4	-	-
UPHM	285.0	Bituminous Shale	15	41	1	34	4	5	-	-
UPHM	361.0	Clayshale	25	69	-	5	-	1	-	-
MPHM	421.0	Bituminous Shale	20	37	2	25	4	12	-	-
MPHM	422.0	Bituminous Shale	14	53	2	23	1	6	1	-
MPHM	481.0	Marlstone	1	66	-	2	-	1	30	-
LPHM	490.0	Bituminous Shale	15	58	1	16	T	9	1	-
LPHM	494.0	Bituminous Shale	17	42	1	27	T	12	1	-
LPHM	500.0	Bituminous Shale	10	36	1	37	3	13	-	-

Stratigraphic Unit	Depth (Feet)	Rock Name	Quartz + Feldspar	Clay	Mica	Organics	Tasmanites	Pyrite	Carbonate	Other
LPHM	509.0	Bituminous Shale	17	37	-	35	T	11	-	-
LPHM	546.0	Clayshale	14	63	7	0	0	2	14	-
LPHM	559.0	Bituminous Shale	14	62	2	19	1	2	-	-
LPHM	590.0	Claystone	12	76	2	1	T	5	4	-
LPHM	602.0	Bituminous Shale	16	40	2	32	3	6	1	-
LPHM	632.0	Bituminous Shale	15	36	3	32	4	5	5	-
LPHM	636.0	Bituminous Shale	8	46	3	19	3	20	1	-
LPHM	662.0	Bituminous Shale	7	36	2	50	1	4	-	-
Drill Hole K-8191 B-2, Herron Testing Labs, Cuyahoga County, Ohio										
CM	17.0	Bituminous Shale	23	53	5	15	T	1	-	3
CM	23.0	Sandstone	59	25	5	10	0	T	-	1
TLM	33.0	Siltshale	35	-	T		-	T	64	1
Drill Hole TX-7, Perry Nuclear Power Plant, Lake County, Ohio										
CS[7]	170.0	Clayshale	19	62	5	5	T	9	T	-
CS	180.1	Mudshale	38	54	3	1	-	2	2	-
CS	190.1	Clayshale	21	70	1	2	-	1	5	-
CS	200.1	Clayshale	4	83	1	1	-	10	1	-
CS	209.9	Claystone	10	88	1	T	-	1	T	-
CS	220.1	Mudshale	35	47	6	2	-	5	5	-
CS	230.0	Clayshale	10	73	3	5	-	7	2	-
CS	239.9	Clayshale	7	79	2	2	-	9	1	T
CS	249.7	Clayshale	14	77	2	1	-	4	2	T
CS	250.0	Siltstone	73	10	4	1	-	2	10	0
CS	259.9	Mudshale	27	56	7	7	T	1	2	-
CS	290.0	Clayshale	3	92	2	1	-	2	-	T
CS	290.2	Clayshale	10	74	2	6	T	8	T	T
CS	320.0	Claystone	13	85	1	T	-	1	-	-
CS	330.0	Claystone	6	83	7	1	-	3	T	-

Appendix - Part A

Stratigraphic Unit	Depth (Feet)	Rock Name	Quartz + Feldspar	Clay	Mica	Organics	*Tasmanites*	Pyrite	Carbonate	Other
CS	339.9	Clayshale	23	55	2	5	-	6	9	T
CS	350.0	Clayshale	17	67	3	6	-	4	3	T
CS	360.0	Clayshale	11	78	2	5	-	4	-	T
CS	370.0	Claystone	16	72	4	T	-	6	2	T
CS	379.9	Clayshale	9	74	2	8	T	6	1	T
CS	389.7	Claystone	6	91	T	T	-	1	2	-
Hell Hole Section, Lake County, Ohio										
CS	Unit #2	Siltstone	89	5	3	1	-	2	-	T
Gulf Park Section, Ashtabula County, Ohio										
CS	Unit #8	Siltstone	75	20	2	1	-	T	0	2
Hadlock Road Section, Ashtabula County, Ohio										
CS	Unit #2	Siltstone	80	3	12	T	-	1	1	3
CS	Unit #5	Siltstone	85	1	3	1	-	T	10	T
Conneaut Creek Section, Ashtabula County, Ohio										
CS	Unit #4	Siltstone	82	10	5	-	-	1	-	-2

1 Please see Table 2 for detailed locations
2 Three Lick Bed
3 Upper part of Huron Member
4 Middle part of Huron Member
5 Lower part of Huron Member
6 Cleveland Member
7 Chagrin Shale

Part B: Samples Whose Type was Estimated by Inspection

Stratigraphic Unit	Depth (Feet)	Rock Name
Drill Hole B-19, Erie County Nuclear Power Plant, Erie County, Ohio		
TLM	30.1	Claystone
TLM	39.7	Claystone
UPHM	51.1	Claystone
UPHM	70.8	Biruminous Shale
UPHM	110.1	Bituminous Shale
MPHM	140.2	Marlstone
MPHM	153.7	Claystone
MPHM	175.6	Bituminous Shale
LPHM	195.6	Bituminous Shale
LPHM	246.4	Bituminous Shale
Avon Drill Hole No. 3, International Salt Company, Lorain County, Ohio		
CM	93.7	Bituminous Shale
TLM	114.3	Siltstone
TLM	178.1	Claystone
TLM	213.3	Siltstone
TLM	258.0	Clayshale
TLM	377.4	Clayshale
UPHM	444.0	Claystone
MPHM	539.1	Claystone
LPHM	598.1	Claystone
LPHM	657.7	Marlstone
LPHM	679.5	Marlstone
Cleveland Hole No. 1 (Whiskey Island), International Salt Company, Cuyahoga County, Ohio		
TLM	165.3	Marlstone
Drill Hole K-8191 B-2, Herron Test Labs, Cuyahoga County, Ohio		
CM	16.0	Sandstone
TLM	31.0	Mudshale

Stratigraphic Unit	Depth (Feet)	Rock Name
Hell Hole Section, Lake County, Ohio		
CS	Unit #2	Siltstone
CS	Unit #2	Siltstone
CS	Unit #3	Carbonate Rock
CS	Unit #6	Siltstone
CS	Unit #12	Siltstone
CS	Unit #18	Siltstone
CS	Unit #19	Siltstone
Gulf Park Section, Ashtabula County, Ohio		
CS	Unit #1	Cone-in-Cone Limestone
CS	Unit #1	Carbonate Rock
CS	Unit #1	Carbonate Rock
Hadlock Road Section, Ashtabula County, Ohio		
Cs	Unit #2	Siltstone
CS	Unit #4	Siltstone
CS	Unit #5	Siltstone
CS	Unit #6	Mudshale
CS	Unit #7	Mudshale
CS	Unit #8	Siltstone
CS	Unit #9	Siltstone
CS	Unit #10	Siltstone
Conneaut Creek Section, Ashtabula County, Ohio		
CS	Unit #4	Siltstone
CS	Unit #6	Siltstone

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